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PERFORMANCES OF HERSCHEL/PACS BOLOMETER ARRAYS AND FUTURE DEVELOPMENTS AT CEA

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Abstract. The European Space Agency is building a space telescope to observe the Universe in the Far-IR and sub-millimeter regime of the electromagnetic spectrum. The scientific payload is composed of three instruments. One of them, PACS, is equipped with a novel type of bolometer arrays developed by CEA in the late 90's. We briefly present the PACS Photometer and the architecture of CEA filled bolometer arrays. We accessed the physics of the detectors and thoroughly measured their performances by developing a pragmatic calibration procedure. The Photometer is now calibrated and integrated on the focal plane of the observatory. The launch is scheduled for April 2009. Meanwhile, CEA is working on adapting PACS bolometers to longer wavelength for wide-field ground-based telescopes, and for the future cold-telescope space mission SPICA.

1 Introduction

The Photodetector Array Camera and Spectrometer (PACS, Poglitsch *et al.* 2004) was calibrated in 2006 at the PI institute in Germany, and it is now integrated on the focal plane of the Herschel Space Observatory (Pilbratt *et al.* 2004) along with the instruments SPIRE (Griffin *et al.* 2006) and HIFI (de Graauw *et al.* 2005). The PACS Photometer is equipped with filled bolometer arrays developed by CEA/LETI and CEA/SAp. These innovative detectors allow to dispense with bulky light concentrators and to instantaneously sample the field of view without altering the optical coupling of the detectors to the telescope beam (Agnèse *et al.* 2003; Billot *et al.* 2006). CEA/LETI opted for an all-silicon design to allow for the collective manufacturing of 16×16 bolometer arrays. Being 3-side

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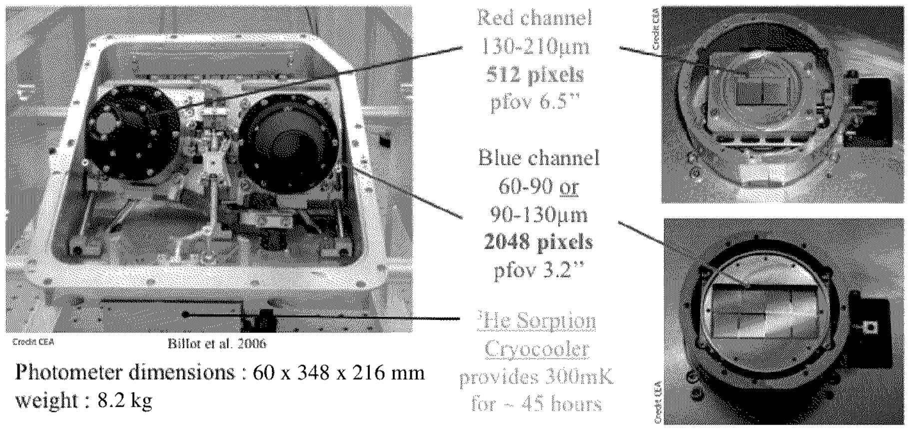

Fig. 1. The Herschel/PACS Photometer Focal Plane Unit is equipped with 10 filled bolometer arrays of 16×16 pixels each.

buttable these arrays are now the building blocks for making large focal planes necessary for the next generation of wide-field sub-mm cameras. We present the unique architecture of CEA filled bolometer arrays and we report on the latest performance measurements of the Herschel/PACS Photometer. We also present current and future developments at CEA for ground-based, balloon borne and space telescopes.

2 The PACS Photometer

The PACS Photometer Focal Plan Unit (PhFPU) is a dual band imaging camera (*cf.* Fig. 1). It uses a cold dichroïc to split radiation between the blue and the red channels operating from 60 to 130 μm and 130 to 210 μm respectively. The focal plane of the PhFPU is made up of a mosaic of filled bolometer arrays (16×16 pixels each) that fully sample the field of view ($1.75' \times 3.5'$ for both channels). The operating temperature of the detectors is 300 mK and the dissipation at this temperature stage is $\sim$5 μW. More details on the PhFPU can be found in Billot *et al.* (2006).

3 Detectors Architecture

CEA bolometer arrays are based on an all-Silicon design that takes advantage of Si micro-machining techniques maturity. This allows the collective manufacturing of arrays containing 16×16 bolometers each, and there is no manual integration step required as it is the case for the manufacturing of traditional bolometers (Turner *et al.* 2001). Unlike most current (sub-)millimeter imagers, CEA bolometer arrays do not use light concentrators to optically couple the detectors to the

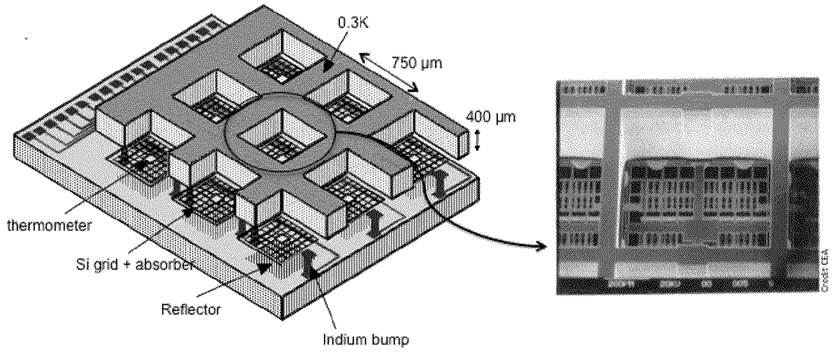

Fig. 2. Schematic view of CEA bolometer arrays (left) and close-up of a pixel (right).

telescope beam but rather a resonant cavity located beneath the absorber to optimize absorption at the operating wavelength. The immediate benefit of using such cavities is the high filling factors achieved by packing pixels closely in the focal plane. This makes the camera very efficient at mapping large areas of the sky (Griffin *et al.* 2002).

CEA bolometer arrays consist of the superimposition of two silicon chips. The detection layer comprises the suspended absorbing grid, the thermometric sensor and the interpixel wall which acts as a heat sink (*cf.* Fig. 2). The readout layer contains the readout electronics which is based on CMOS technology and runs at 300 mK. This circuitry provides a 16-to-1 multiplexing function to reduce the number of electric lines, and therefore reduces the heat load on the 300 mK stage ($\sim$5 μW dissipation). A reflecting gold sheet is also deposited on the readout layer in order to create a standing wave, and ensure that 100% of the electromagnetic radiation energy is in the form of an electric field at a location $\lambda/4$ above the readout layer. The two layers are then hybridised with Indium bumps to establish electrical and thermal contact. The diameter of the indium bumps sets the size of the resonant cavity. In the case of PACS bolometer arrays, the bumps diameter is 20 μm. More details on resonant cavities and actual absorption measurements can be found in Revéret *et al.* (2008).

The bolometer signal is read at the middle point of a resistor bridge; one resistor is thermalized at the interpixel wall temperature (300 mK) and the other is implanted in a mesa configuration in the middle of the absorber to detect temperature variations. More details can be found in Billot *et al.* (2006).

4 Calibration and Performances

4.1 Calibration Procedure

Most bolometers are calibrated by measuring the current flowing through individual thermistors as a function of the voltage applied across them, and by fitting

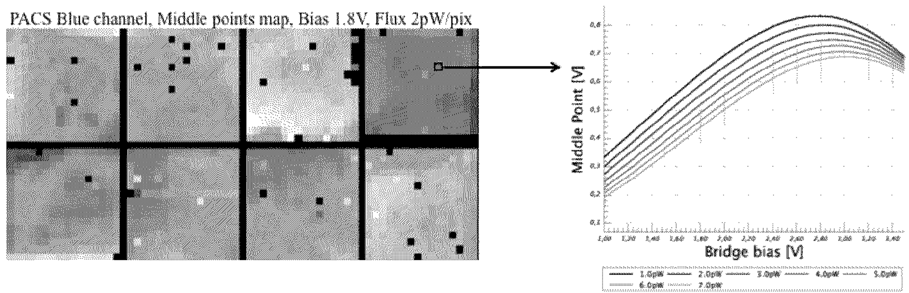

Fig. 3. Middle point map for a given set of bolometer bias voltage and optical load on the blue channel of the PhFPU (left). Individual sub-arrays are separated by approximately 1 pixel. Dead pixels represents only 2% of the blue channel. Evolution of a pixel middle point as a function of bias voltage and optical load (right).

these I-V curves (often called load curves) with an analytical model of the detectors to extract their physical parameters (Griffin & Holland 1988; Turner *et al.* 2001). However, in the case of CEA bolometer arrays, this standard method is inapplicable to individual pixels since we cannot access the current flowing through individual bolometers (reference resistors cannot be considered as known current sources as their impedance depends on the optical load through electric field effects). We developed a pragmatic calibration procedure based on the retrieval of bolometric bridge middle points. These quantities are independent of the readout electronics and represent the electrical state of each bolometric bridge. To access middle points and correct for the various offsets of the readout electronics, we measured the transfer function of the whole electronics chain by injecting known reference voltages at different stages of the readout electronics. We built a complete dataset of middle points for each pixels to predict their behavior for any given bridge bias and optical load (*cf.* Fig. 3). This information was used to automate the fine tuning of the readout electronics offsets. We successfully applied our procedure during the PACS calibration campaign to test thousands of configurations of the system while minimizing saturation issues (Billot *et al.* in prep.).

4.2 Bolometer Array Performances

4.2.1 Time Constant

We measured the bolometers response time in the time- and Fourier-domain (*cf.* Fig. 4).

- We use two warm black bodies and a chopper to measure the evolution of the signal amplitude as a function of the modulation frequency. The faster the modulation, the smaller the amplitude. The low-pass cutoff frequency is defined as the frequency at which the amplitude is attenuated by 3 dB.

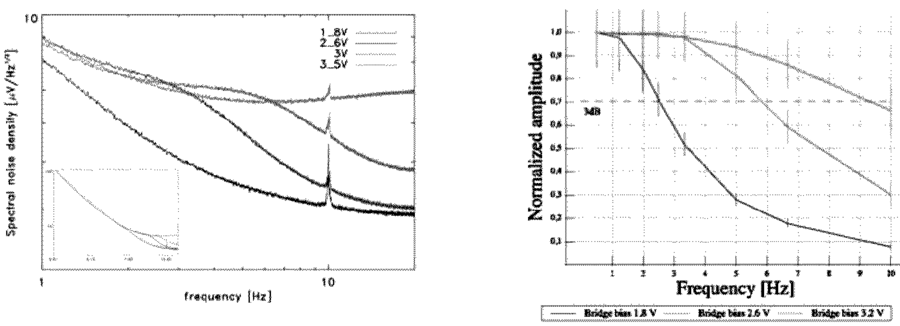

Fig. 4. Bolometers response time in Fourier-space (left) and in real-space (right).

- The spectral noise density contains the imprint of the low-pass filter. We extract the cutoff frequency by fitting the spectrum with a simple model.
- The time constant τ and the cutoff frequency ν_c are related by $\tau = \frac{1}{2\pi\nu_c}$.

Both methods yield similar time constants of the order 20–40 ms depending on the bias voltage applied across the bolometric bridges. The higher the bias voltage, the faster the bolometers respond to flux changes.

4.2.2 Sensitivity

We measured the detectors sensitivity, or Noise Equivalent Power (NEP) for various configurations of bolometer bias voltage and optical load (*cf.* Fig. 5).

We find that the optimum setting of PACS bolometer arrays is a trade-off between sensitivity and rapidity. As an example, for a bias voltage of 2.7 V on the blue channel bolometers, we measure a time constant of $\sim$30 ms, a noise level of 6 $\mu\mathrm{V}/\sqrt{\mathrm{Hz}}$ and a responsivity of 3×10^{10} V/W, resulting in a NEP of 2×10^{-16} $\mathrm{V}/\sqrt{\mathrm{Hz}}$.

5 Future Developments

5.1 Space Instrument: SPICA/SAFARI

The Japanese Space Agency JAXA is building a Far-IR space telescope named SPICA (Kaneda *et al.* 2004). The dish will have a diameter of 3.5 m, as for the Herschel Observatory, and will be actively cooled to 4–5 K, reducing considerably the background emission from the telescope.

CEA is proposing a new detector design to meet sensitivity requirements of the SPICA / SAFARI instrument:

- Bow tie antenna located $\lambda/4$ above reflector to absorb EM radiation.
- Capacitive coupling between antenna and suspended load resistor.

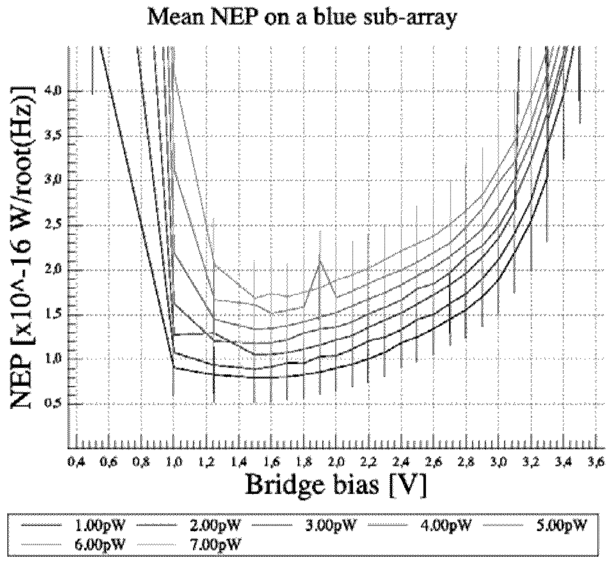

Fig. 5. Evolution of a PACS blue channel bolometer array sensitivity as a function of the bias voltage applied to the detectors and the optical load.

- Reduce heat capacity by reducing suspended mass (no silicon grid, no metal absorber) and operating the detectors at lower temperatures.
- Increase thermal resistance by thinning suspending rods to 20–100 nm and by operating the detectors at 50–100 mK.
- High electro-thermal response using Si:P:B thermometers at 50–100 mK.
- Time Domain Multiplexing based on CMOS or Quantum-Point-Contact HEMT operating at 50–100 mK.

New absorption computations for bow tie antennae with Òair gapÓ cavity on reflector show promising results. More details on the design of these antenna bolometers developed by CEA can be found in Agnèse 2008 (these proceedings).

5.2 Ground-Based: ArTèMiS

ArTéMiS is a wide-field sub-mm camera designed for the APEX telescope. its forseen installation date is 2010. ArTéMiS will be capable of simultaneous imaging at 200, 350 and 450 μm with a total of 5560 bolometers (20 arrays of 16×18 pixels). The instrument features an autonomous cooling system using a pulsed tube and a ^{3}He-^{4}He sorption cooler. More details on the design of ArTéMiS can be found in Talvard *et al.* (2008).

The prototype instrument, P_ArTéMiS, which is equipped with a modified PACS bolometer array optimized to absorb radiation in the 450 μm window

(Revéret *et al.* 2008, these proceedings), has already been tested on KOSMA and APEX telescopes. These test runs demonstrated the relevance of the CEA bolometer arrays concept. André *et al.* (2008) observed the high-mass star forming region NCG 3576 at 450 μm with P_ArTéMiS on APEX.

5.3 Balloon-Borne: PILOT

PILOT is a balloon-borne experiment aiming at measuring the polarization of the ISM at 240 and 550 μm to prepare for future Cosmic Microwave Background polarization missions. PILOT will be equipped with 8 modified PACS bolometer arrays, a 83 cm telescope, a payload of 700 kg. The first flight is scheduled for 2010 (Bernard 2005).

6 Conclusions

In these proceedings, we have briefly presented the architecture of CEA bolometer arrays and the calibration procedure we developed to access the physics of the bolometers. These detectors are now integrated in the PACS Photometer and have been calibrated for photometry before delivery to ESA. The measured sensitivities and time constants are within the specifications. Scientific results are already being produced using the P_ArTéMiS instrument on the APEX telescope demonstrating the relevance of the CEA filled bolometer arrays concept. With many projects in prospect, the future of these detectors looks very bright.

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